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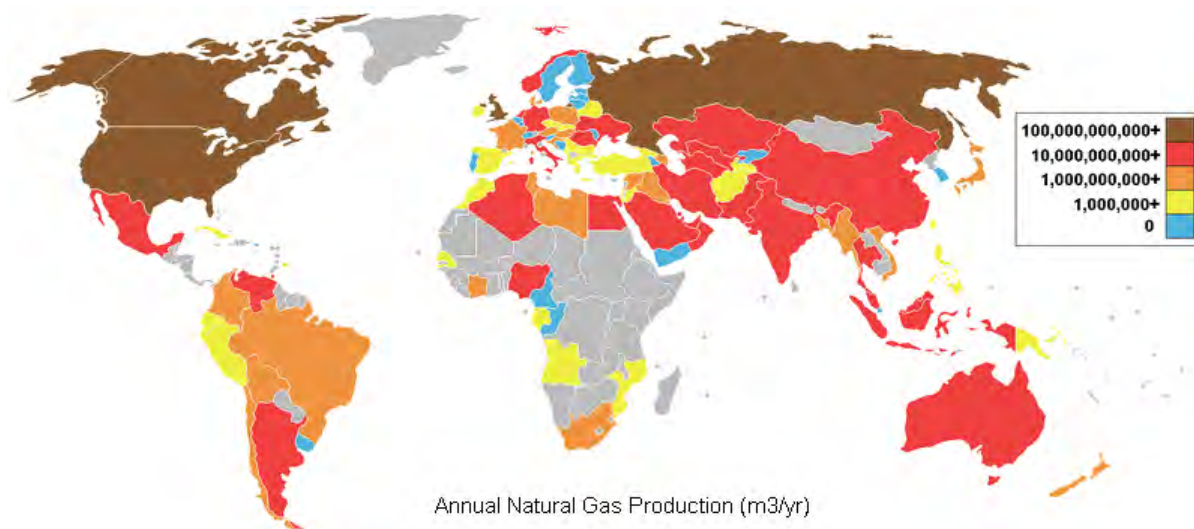
## Natural Gas Propulsion Options for Short Sea Shipping Routes

By

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## Abstract

*With strict emission rules and regulations coming into place, natural gas presents itself as a favorable option in helping to reduce the amount of harmful emissions compared to diesel fuel. A team has been assigned to assess the performance, weight, safety, and volume implications of a range of various natural gas systems for a vessel designed for short sea shipping, which is an interest of the American Marine Highways Program. The vessel is currently being designed under the sponsorship and direction of the Center for Commercial Deployment of Transportation Technologies (CCDoTT) by Herbert Engineering Corporation (HEC). The focus of this document is to outline the various natural gas systems, storage options and implications resulting from the installation of these systems aboard a vessel.*



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## Acronyms

ABS	American Bureau of Shipping
AMHP	America's Marine Highways Program
CCDoTT	Center for the Commercial Deployment of Transportation Technologies
CNG	Compressed Natural Gas
DF	Dual-Fuel
DNV	Det Norske Veritas
ESD	Emergency Shutdown System
GPA	Gas Processors Association
GVU	Gas Valve Unit
HEC	Herbert Engineering Corporation
HFO	Heavy Fuel Oil
IGC	Int'l Code for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF	International Code of Safety for Gas-fuelled Ships
IMO	International Maritime Organization
LCG	Longitudinal Center of Gravity
LNG	Liquefied Natural Gas
MDF	Marine Diesel Fuel
NDF	Natural Defense Funds
NECA	Nitrogen-oxide Emission Control Areas
NFPA	National Fire Protection Association
NREIP	Naval Research Enterprise Intern Program
NG	Natural Gas
RORO	Roll-on/Roll-off
SCR	Selective Catalytic Reduction
SECA	Sulfur-oxide Emission Control Areas
VCG	Vertical Center of Gravity





## Introduction

### *Objective*

Liquefied natural gas (LNG) carriers have been using boil-off gas as an additional fuel source for years. Consequently, dual-fuel engines that are operable both diesel and natural gas (NG) have been designed and are readily available on the commercial market. The use of NG as the main fuel introduces many benefits, but many technical difficulties related to the vessel design, safety, and availability are also introduced. The purpose of this report is to outline the benefits of using NG as a main fuel source and to study the implications of an NG fuel system on the design and operations of a commercial vessel.

### *Background*

There is currently a strong interest in the development of short sea shipping routes along U.S. coastlines and inland waterways. The goal of these trade routes is to replace some long truck hauls, particularly along the coastlines. By transporting trucks on the water rather than on land, significant decreases in congestion and environmental impact may be achieved, particularly in urban areas. For this option to be commercially viable, the ships must be able to operate at a cost and schedule comparable to existing truck transport. There also exists a potential for these vessels to be used for military sealift operations when necessary.

Additionally, due to increasingly stringent environmental regulations these vessels must exhibit significant reductions in greenhouse gases and other pollutants. While some improvements to a vessel's emissions may be made through the use of exhaust scrubbers, the largest impact can be made by selecting a cleaner fuel source. One such fuel is NG, which is becoming increasingly available to the marine industry via trade ports and filling terminals. NG offers significant advantages compared to diesel fuel; however, in order to be utilized as a main fuel source, its storage and safety implications must be thoroughly understood.

### *Project Directives and Constraints*

The purpose of this report is to outline the implications of using NG as a marine fuel. The study has been completed in accordance with the following directives: (1) the main requirement states that the RORO container/trailer carrier should use natural gas as its main fuel source for operations along the east coast, (2) the fuel systems should meet all applicable classification and governmental rules and regulations, and (3) the converted design must maintain the same speed and range requirements as the original vessel.

Additionally, the emissions of the vessel and fuel consumption should be reduced as much as possible, and an assessment of the impact on the life-cycle cost of the vessel as a result of conversion to natural gas shall be performed. The vessel should be flexible to allow military use, and cargo areas should be maintained (i.e. no machinery in cargo





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areas). Regarding the storage options of natural gas, an additional concept for innovative storage of LNG and CNG will be considered during this study.

The following deliverables have been completed:

1. A study of the impact of the conversion of a short-sea shipping vessel to run on natural gas
2. Development of concepts for major modifications to the vessel that may greatly facilitate the installation of natural gas on board, and improve the overall vessel efficiency
3. An exploration of the possibility of a fully LNG-powered vessel as opposed to a dual-fuel power plant

Finally, the candidate systems should not introduce a significant amount of additional weight to the ship, overall vessel dimensions should not be altered, the cost of the vessel should not be increased significantly, and the existing cargo capacity must not be decreased too drastically in order to remain financially viable.

## Problem Statement

### *AMHP and CCDoTT*

America's Marine Highway Program (AMHP) aims to reduce the amount of cargo transported via land-based highways using trucks. It has been found that trucks account for almost 40 percent of the time Americans spend stuck in traffic [1]. By reducing the amount of traffic on the highways, a significant overall reduction in hazardous emissions and the formation of greenhouse gases can be achieved. In support of these interests, the Center for the Commercial Deployment of Transportation Technologies (CCDoTT) is sponsoring and directing an effort with Herbert Engineering Corporation (HEC) to design a roll-on/roll-off (RORO) container/trailer carrier for use in short-sea shipping. For this vessel, HEC is evaluating the advantages and design issues associated with the use of natural gas (NG) as the vessel's primary fuel source. Due to possible interest from the US Navy, HEC began a collaborative effort with the Center for Innovation in Ship Design (CISD) in order to more thoroughly explore this option.

### *Principle Characteristics*

HEC has recently completed the preliminary design of a RORO container/trailer carrier for use in short-sea shipping. This design was used as a baseline to be evaluated for the installation of natural gas system. The principle characteristics and dimensions of the vessel are shown in Table 1. More specific information about the design is located in Appendix A.

Item	Dimension	Unit
Length, overall	180.3	[ m ]
Beam	36.6	[ m ]
Design Draft	6.7	[ m ]
Design Speed	18	[ knots ]
Power Required	19,400	[ kW ]
RORO Area	16,500	[ m <sup>2</sup> ]
Propulsion, Twin Screw	Diesel-Electric	

**Table 1: RORO container carrier characteristics**

### *Operating Modes*

The container/trailer carrier is designed to support two different operating modes. The first mode is normal operation, which includes traveling a range of approximately 3,000 – 5,000 nm while using natural gas for propulsion. This mode is strictly applicable for operations on the eastern coast while delivering and receiving containers and trailers.

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During this mode, the vessel is expected to refuel after two round trips, which corresponds to the 5,000 nm required range.

The second mode consists of traveling a maximum range of 10,000 nm to supplement military operations. This includes transoceanic travel and additional missions. In the case that the vessel was called upon for military options, minor modifications would be made to these vessels under the Department of Defense's Natural Defense Funds (NDF) to support emergency deployment and sustainment of U.S. military forces.

### LNG Characteristics & Benefits

Natural gas has already found many uses and many homes are now heated using gas. NG is a less complex hydrocarbon than diesel fuel, making the processing and emissions a lot cleaner. It is primarily composed of methane, as shown in Figure 1, but also contains small amounts of ethane, propane, and other gases. It is typically stored either as a compressed gas (CNG) or in liquefied form (LNG) and its composition varies accordingly.

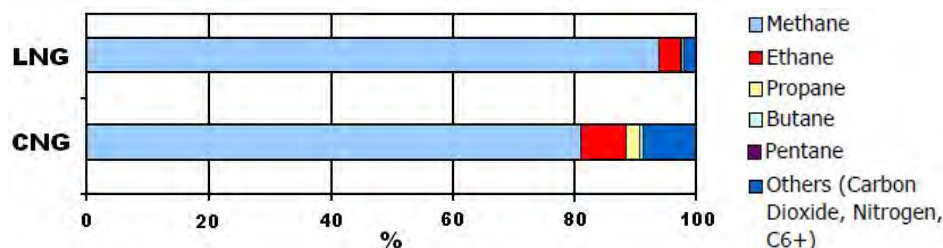


Figure 1: Chemical composition of natural gas [13]

According to the Center for Energy Economics, LNG is cryogenically stored at a temperature of approximately -259°F (-162°C) and maintains a liquid state by evaporating a small amount of gas to cool itself. Compared to natural gas at atmospheric pressure, LNG containing the same amount of energy takes up approximately 1/600<sup>th</sup> the volume. In contrast, the volume of compressed natural gas is dependent on the pressure at which it is stored. Since the maximum storage pressure typically available is approximately 275atm, the volume of compressed natural gas (CNG) required for the same amount of energy is more than twice that of LNG. To highlight this difference, the amount of diesel, CNG and LNG required for the HEC vessel to travel 1,000nm is compared below in Figure 2.

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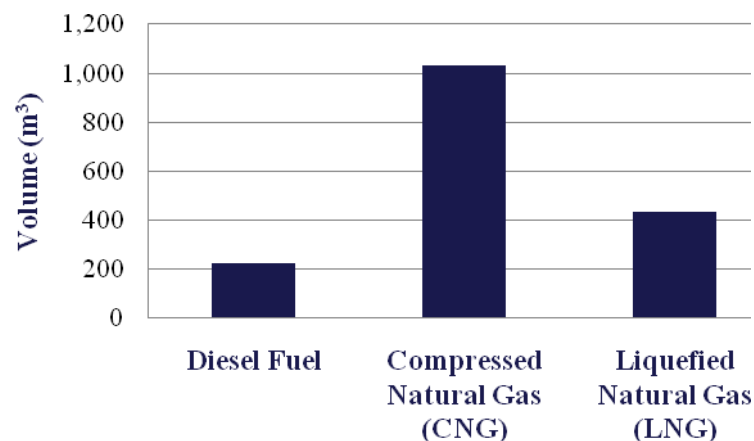


Figure 2: Comparison of required fuel volume for 1000 nm range

The ignition temperature varies from 1,000°F for LNG and 1,350°F for CNG. Due to these high temperatures, the gas must be ignited by a diesel pilot fuel in order to be combusted in a dual-fuel engine. The density of LNG varies slightly with its specific composition, but ranges from approximately 430 kg/m<sup>3</sup> to 470 kg/m<sup>3</sup>, roughly half the density of diesel fuel. LNG is colorless, odorless, non-corrosive, non-flammable and non-toxic. When LNG reaches its boiling temperature, it evaporates quickly into a vapor cloud that will rise above air.

A primary advantage of LNG is its reduced emissions when used as a marine fuel compared to heavy fuel oil (HFO) and marine diesel oil (MDO). Due to its simpler composition, LNG has been shown to reduce carbon dioxide (CO<sub>2</sub>) emissions by 20%, nitrous oxide (NO<sub>x</sub>) emissions by 80%, and produces almost no sulfur oxide (SO<sub>x</sub>) or particulate emissions. Consequently, LNG is a very attractive option for meeting future emission requirements.

A final, more long-term, benefit is that NG can more easily be used to power fuel cells. Since it is a simpler hydrocarbon than diesel fuel, it requires much less processing than diesel fuels.



## Rules and Regulations

### *Applicable Documents*

Natural gas is becoming an increasingly important fuel in the marine sector, yet it is still considered to be a “new” fuel trend within the commercial industry. Complete and thorough rules and regulations that can be directly applied to vessels using natural gas as a primary fuel are relatively nonexistent; however, there are organizations that are currently working on developing the “*International Code of Safety for Gas-fuelled Ships*,” (IGF Code) which will provide more specific guidelines in the near future.

The current set of rules applicable to natural gas-powered vessels is titled “*Interim Guidelines on Safety for Natural Gas-Fuelled Engine Installations in Ships*” (Resolution MSC.285(86), adopted 01 June 2009), which was created by the International Maritime Organization (IMO). This document recognizes that, since natural gas is becoming a more widely used fuel in the marine industry, there exists a need for the development of a code for primarily gas-fuelled ships. As such, it provides regulations that are appropriate for general arrangements, system design, fire safety, and electrical systems for natural gas-powered vessels.

Another set of applicable rules have been created by the classification society Det Norske Veritas (DNV) entitled “*Gas Fuelled Engine Installations*.” This document includes specific details that are applied to internal combustion engine installations in ships; however, it specifically applies to requirements for LNG carriers.

Additional documents that do not directly apply to the design, but were researched, are listed below. A majority of these documents specifically apply to LNG cargo carriers only, but the knowledge contained with regards to handling of LNG was found to be useful.

1. “International Code for the Construction and Equipment of Ships Carrying Liquefied Gases and Bulk” (IGC Code, MSC. 4 (48) 2003)
2. “Dual Fuel Engine Safety Concept for LNG Carrier Applications” – Wärtsilä Corporation (2010)
3. “Guide for Propulsion Systems for LNG Carriers” – American Bureau of Shipping (2005)

### *Emission Regulations*

In addition to AMHP, which aims to reduce the emission levels on land, the International Maritime Organization (IMO) has passed several resolutions detailing emission requirements that will have to be met within the next few years on water. These requirements aim to reduce the amount of pollution caused by maritime vessels by



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placing restrictions on the specific emissions of nitrous oxides ( $\text{NO}_x$ ), one of the major causes of acid rain.

As presented in Wärtsilä's Greentech Presentation [17], the first set of IMO restrictions will be applied to vessels constructed beginning in the year 2011. This emissions level, known as Tier II, corresponds to a  $\text{NO}_x$  reduction of 20% and can be reached by relatively minor changes to engine operating procedures and by engine optimization. The next level, IMO Tier III, introduces a further reduction of 80% from today's  $\text{NO}_x$  emissions standard and will be required by the year 2016. To meet this requirement, more drastic measures must be taken such as the selection of an alternative fuel or the installation of a selective catalytic reduction (SCR) system. These SCR systems are typically very heavy, expensive, and take up a lot of space. Therefore, alternative fuel types such as LNG are an attractive option. A comprehensive graph describing these emission requirements is shown below in Figure 3.

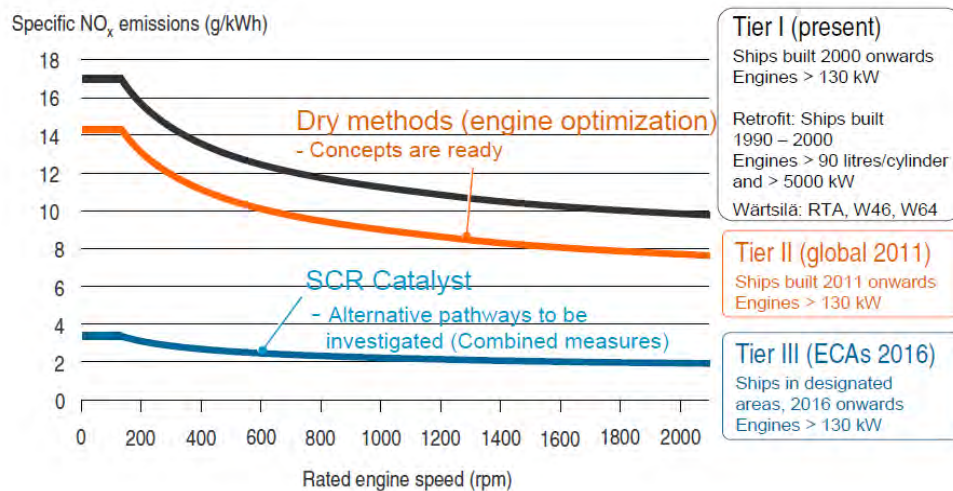


Figure 3: IMO emission requirements [17]

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In addition to the Tier I, II, and III requirements, IMO has defined NO<sub>x</sub> and SO<sub>x</sub> Emission Control Areas (NECA & SECA, respectively). These areas constitute coastal regions and are constrained to even further emission requirements. In North America, the NECA and SECA areas are located 200 nautical miles off of the coastlines, as shown in Figure 4.

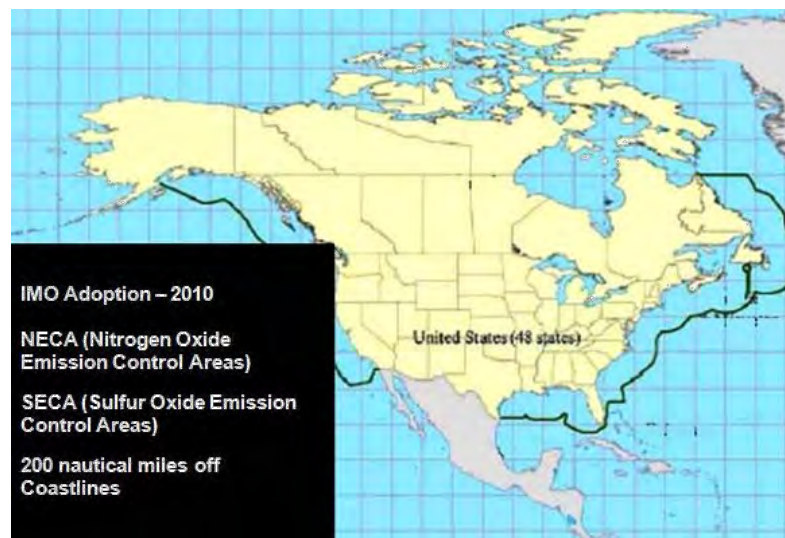


Figure 4: Additional IMO emission control areas [17]



## Operational Issues

### Safety

There are a number of safety hazards related to the use of natural gas, including risk of explosions, vapor clouds, freezing liquids, rollover, rapid phase transition, and terrorism concerns. These safety hazards can be controlled by taking the necessary safety precautions outlined in the rules and regulations previously discussed. Within each specific system, these hazards must be recognized and actions must be taken in order to reduce risk. For example, for an LNG container carrier, the design is most concerned with the risk of explosions, vapor clouds, freezing liquid, and rapid phase transitions of LNG, so these risks must be designed against.

The requirements to ensure safe operation of LNG include primary containment, secondary containment and safeguard systems, all of which are related and controlled by industry standards/regulatory compliance. The following relationship map in Figure 5 is an alteration of a system that was created and published in “LNG Safety and Security,” from the Center for Energy Economics [13].

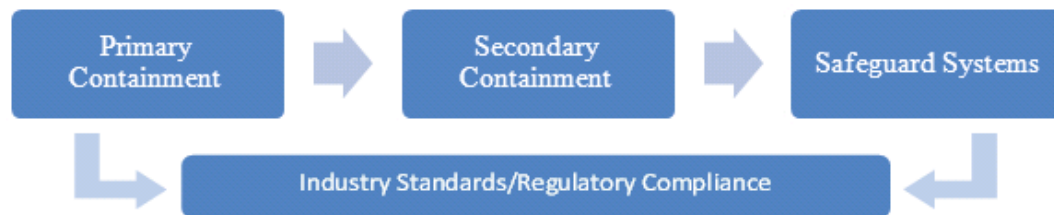


Figure 5: Safety relationship map [13]

The Center for Energy Economics describes the primary containment as the first and most critical requirement for LNG to be safely kept. This is accomplished by using appropriate materials for the first protection layer of LNG tanks and other equipment involved in the system. The material used for this protection layer is typically stainless steel. Critical and accurate engineering design of LNG storage is also required in the primary containment.

Secondary containment is the protective layer that ensures LNG is contained in the case of a leak or spill. This includes the second layer that surrounds the primary layer of LNG onboard a vessel. These containment systems exceed the volume of the primary storage tank. Secondary containment prevents LNG leaks or spills from affecting the surrounding environment and being exposed to nearby structures. Additionally, this secondary barrier prevents the ship’s structural temperature to be lowered to a level that may cause structural failure.

The third layer of protection consists of the safeguard systems. The primary goal of this layer is to minimize the release of LNG in the case of a leak or a spill. It is also



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used to detect and locate the area where the accident is occurring. For this level of safety protection, LNG operations utilize gas, liquid, and fire detection to identify a breach in the containment systems. Remote and automatic shut off systems are also used to minimize leaks and spills in the case of an emergency. Human interactions during procedures, training, and emergency responses are also used to help prevent hazards. In order to keep all of these systems efficient and reliable, frequent maintenance procedures and checkpoints are required.

None of these protection systems are accurate without verification that maintenance procedures and appropriate operating steps are in place. Additionally, responsible personnel need to be trained to have the ability to act immediately in the course of an accident. The Center for Energy Economics leaves the tasks of maintaining these procedures and verifying that all systems are up to date to industry standards and regulatory compliance organizations. Some example organizations include the National Fire Protection Association (NFPA) and the Gas Processors Association (GPA).

### *Double Bottom*

There is currently no specific rule that requires LNG powered vessels to have a double bottom. However, since LNG storage tanks are considered a hazardous gas area, they are required to be in a gas safe separate compartment according to IMO rules and regulations. During the design process, HEC came to the conclusion that the tanks need to be located away from the side of the ship in order to prevent heating from the outside when the vessel is operating in high ambient temperatures; therefore a double bottom was deemed appropriate for the RORO container/trailer carrier. Specific details on gas safe compartments can be found in the IGC Code.

### *Handling*

Several sources provide rules and requirements that must be followed during the refueling process in order to prevent emergencies from occurring. The main focus of these requirements is to protect the vessel from exposure to extremely cold temperatures, to prevent gas from leaking to the outside environment and to prevent human contact during these transactions.

IMO guidelines state that the bunkering station should be physically separated from accommodations, control stations, and working/cargo decks. The connections and piping need to be positioned and arranged such that, in the case of any possible damage to the gas piping, the vessel's gas storage tank arrangement will remain unharmed. This will prevent uncontrolled gas discharge from occurring in the event of an accident.

Additionally, drip trays are required to be fitted below the liquid gas bunkering connections and under any other areas where leakage may occur. The drip trays are composed of stainless steel and shall be drained over the ship's side by a pipe that leads down near the sea. The surrounding deck structures and hull need to be protected from unacceptable cooling during this process in case of leakage of liquid gas in order to



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prevent material damage within the ship structure. For compressed gas bunkering stations, steel shielding at low temperatures should be used in order to prevent the escape of cold jets onto the surrounding hull structure.

## Control Systems

IMO guidelines state that supervision of the control systems needs to be made from a safe location in relation to the bunkering operations. The tank pressures and tank levels should also be monitored during the process. At this location, overfill alarms and automatic shutdown must also be incorporated.

There exists an Emergency Shutdown System (ESD) associated with shut-off valves to ensure the safe and rapid shutdown of the LNG transfer during an emergency. The system has the ability to stop the ship's unloading pumps by closing both flow valves on the ship and on the fuel supplier. This action limits the chances of an accidental release to only a few hundred gallons of LNG, rather than many more. It is estimated that the ESD system has the ability to close the flow valves within 20 to 30 seconds.

A remote operated shutdown valve and a manually-operated stop valve in series, or a combined manually-operated and remote valve should also be fitted within every bunkering line close to the shore connecting point. It should be designed so that the remote-operated valve can be closed or released in the control location for bunkering operations.

## Fire Safety

A dry chemical powder extinguishing system should be permanently installed in the bunkering station area to cover all possible leak points. The system is also required to be designed for accessible and feasible manual release from a safe location outside the protected area. The dry chemical powder extinguishing system should be at least 3.5kg/s for a minimum of 45 second discharges. In addition, one portable dry powder extinguisher with at least 5 kg capacity should be placed near the bunkering station.

More details of the bunkering control systems, ventilation requirements, and fire safety are located in Chapter 2 of IMO's *"Guidelines on Safety for Natural Gas Fuelled Engine Installations in Ships."*

## Training

There are extensive training requirements for persons involved with natural gas powered vessels that are stated within IMO guidelines. The entire operational crew is required to have necessary training in gas related safety, operations, and maintenance prior to the commencement of work onboard in order to verify that under any sort of emergency situation, the crew will be able to successfully act and take part in an immediate response. All will receive specific LNG training in firefighting, cargo



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handling, and relevant safety systems, including drills on various scenarios related to the vessel itself.

There are three separate categories of training requirements:

1. Category A – Training for basic safety crew
2. Category B – Supplementary training for deck officers;
3. Category C – Supplementary training for engineer officers.

Category A training is based on the assumption that the crew has no prior knowledge of gas and the related engines and systems. The training focuses on teaching basic crew the following specifications: the basic understanding of the gas in question as a fuel, technical properties of both compressed and liquid gas, ignition sources, and rules and procedures that need to be followed in both normal operations and in emergency situations. The training consists of theoretical and practical exercises that are involved with gas and the relevant systems, along with personal protection issues that come into effect when handling both compressed and liquid gas. Practical extinguishing of gas fires also takes part in the training process at an approved safety center.

Categories B and C training is divided technically between deck and engineer officers, and both groups receive gas training beyond the general training. The company's training manager and the master are those who will determine what comes under engineering and what comes under deck operations. Additional details of these training requirements are located in Chapter 8 of IMO's "*Guidelines on Safety for Natural Gas Fuelled Engine Installations in Ships.*"

## Operations

Dual-fuel (DF) engines are readily available and can operate on either diesel fuel or natural gas. Under certain limitations, the operating mode can be changed while the engine is running without interruption of power generation. In the case of the gas supply failing, the engine is capable of automatically transferring to diesel mode operation. DF engines are required to be started and stopped on diesel mode, and the engine can use either marine diesel fuel (MDF) or heavy fuel oil (HFO) provided that the fuel system and engine are properly preheated.

The Wärtsilä 34DF Project Guide describes that in gas operating mode, natural gas is the main fuel that is injected into the engine at a low pressure. The gas is ignited by injecting a small amount of pilot fuel. When running on natural gas, dual-fuel engines are restricted to a three minute idling time to prevent a situation of incomplete combustion. If the engines operate below 15% for more than three minutes, the system will automatically transfer into diesel mode. If the engine is running in gas mode at above 15% load, there are no operational restrictions.

During diesel mode operation, the engine is allowed to be started, stopped, and operated under all operating conditions and behaves like any standard diesel engine. The



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following are specific details from the engine project guide on different operating conditions:

- Absolute Idling (disconnected generator)
  - Maximum ten minutes if the engine needs to be stopped after idling
  - Allow three to five minutes in idle mode before the stop is recommended
  - Maximum six hours if the engine is to be loaded after the idling.
- Operation Below 20% Load
  - Maximum 100 hours continuous operation
  - At intervals of 100 operating hours, the engine must be loaded to minimum 70% of the rated output
- Operation Above 20% Load
  - No restrictions.

The blackout detection system, or the engine control and safety system, can transfer the engine to backup operation mode in some situations; this mode is only operating on diesel fuel. During this time, the diesel pilot injection system is not active. A maximum time of 30 minutes is allowed in backup operation mode.

## Ventilation

Rules and regulations require that each room containing or handling NG must be mechanically ventilated. These spaces are also required to be designed such that, in the event of a gas leak, gas buildup in a corner or enclosed area is avoided. To monitor gas leaks, gas detectors are required in each gas-enclosed room. The ventilation for each room is required to have a capacity of 30 air changes per hour. For the HEC design, this results in a tank room capacity of approximately 7,300m<sup>3</sup>/min and an engine room capacity of approximately 3,800m<sup>3</sup>/min.

All ventilation systems must have at least two fans of non-sparking construction where the capacity of each individual fan meets the total required capability for that system. The gas ventilation systems must be fully independent of other installed ventilation systems such that all leaked gas is transferred to a safe location without joining any other ventilation system. The ventilation ducts must also be smoothly constructed in order to avoid any gas buildup while being transported to a safe zone. In addition to the engine room ventilation systems, the crankcase for each engine is individually vented. The gas from the crankcase is transferred to a safe location through a flame arrester.





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The IMO Guidelines also state that the bunkering station should be located in an area where there is sufficient natural ventilation. In the event that the ventilation in the ducting located around the gas bunkering lines stops, a visual and audible alarm should be provided at the bunkering control location.

### *Fueling Locations*

While there are several LNG import terminals sprouting across the country (Everett, MA, Cove Point, MD, Elba Island, GA, and several locations in the Gulf), to date no actual LNG refueling stations have been built. Currently, there are joint efforts pushing for the construction of LNG refueling stations along the eastern coast, but these efforts have been counteracted by groups who consider LNG to be a dangerous fuel and a threat to national security. Appendix C includes specific locations for LNG import terminals, both existing and proposed.

Currently, the simplest option for refueling LNG is to transport it directly to the port via fueling trucks with capacities from 20-40m<sup>3</sup> each. From these trucks, the ship can be directly refueled at an average rate of 40m<sup>3</sup>/hr. At the given rate, the estimated refueling time for the container/trailer carrier's six 256m<sup>3</sup> tanks being simultaneously refueled is approximately 6.4 hours, however the actual fueling time will be dependent on the number of tanks being filled simultaneously.

To shorten the refueling time, the RORO container/trailer carrier has the option of carrying 21 ISO containers on the open deck with the other containers. This number of ISO containers can store the required amount of LNG to operate in gas mode for one round trip on the eastern shore. With ISO containers, several tanks would be waiting at the ship's destination, and the refueling time would only consist of loading the containers onto the top deck and connecting the supply lines. The use of ISO containers would save refueling time as well as costs, and would also significantly reduce the ventilation requirements.

### *Maintenance*

Concerning the maintenance of dual-fuel engines, the arrangements and systems are straightforward. There have been design minimizations of piping and external connections for simplicity, an electronic safety protection system is built in, and the maintenance of the overall system is easy and quick. Additionally, the clean-burning nature of NG greatly improves the engine's maintenance requirements, in some cases doubling the time between overhauls.



## Leading Concept

### *Functional Decomposition of Main and Auxiliary Systems*

The main engines are supported by several auxiliary systems. The auxiliary systems installed on the concept ship are crucial in maintaining safety, functionality and overall cleanliness. These systems perform such jobs as handling the LNG, supplying the marine diesel fuel (MDF), distributing the lube oil, and utilizing the compressed air for startups.

LNG is cryogenically stored in four tanks at a pressure of 5bar and a temperature of -259°F. Because of the pressure that the LNG is stored at, a pump is not required to transfer the gas out of the tanks. The LNG is directed through an evaporator, where it is heated into a gaseous state and is then led to the Gas Valve Unit (GVU). The primary purpose of the GVU is to regulate the pressure of gas to the engine inlet.

The gas is directed through a fine filter to keep any impurities from reaching the engine. A fuel gas pressure regulator is then used to keep the pressure in accordance with the engines load. The GVU also includes a manual shut-off valve, purging connections, shut-off block valves, ventilating valves, and pressure gauges. All of these items are included for the safety of the system and to avoid any pressure or gas buildups within the GVU.

Due to the high ignition temperature of natural gas, a diesel pilot fuel (MDO) is used to initiate combustion. Overall, approximately 1% of the total fuel consumption is attributed to the diesel pilot fuel. In times of an LNG shortage, the dual-fuel engine will automatically switch its fuel intake to run completely on diesel. The ship is also equipped to run 100% diesel fuel for a maximum range of 10,000 nautical miles.

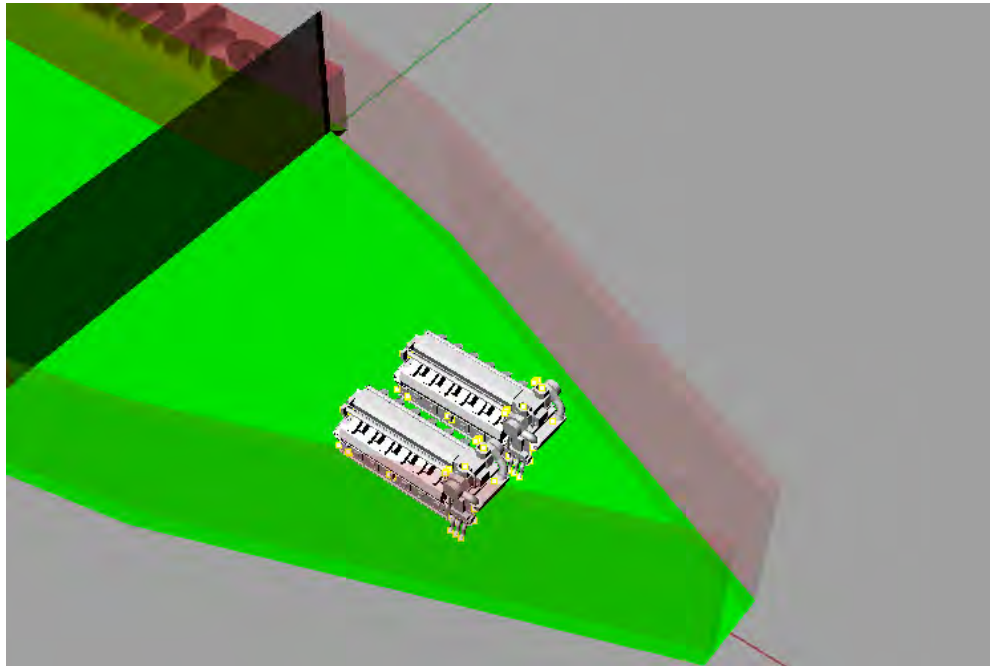
The ship is supplied with a compressed air system for engine starting, which is stored in compressed air storage cylinders. The system leads compressed air through a valve directly into the cylinder heads at 30bar to begin the rotation of the engine. After this rotation occurs, the engine is supplied with diesel fuel until it reaches its optimal load.

### *Dual-Fuel Engines*

The design concept was initially powered by with two large 12V50DF Wärtsilä engines, which is shown in Figure 6. These were placed side by side and located in the forward machinery room to leave additional space for any auxiliary systems that were needed. However, the performance of this preliminary machinery layout in the event of an engine breakdown was seen to be an issue since the ship would lose half its power. In order to maintain near normal operations in these situations, it was decided that the ship should be supplied with a larger number of smaller engines.



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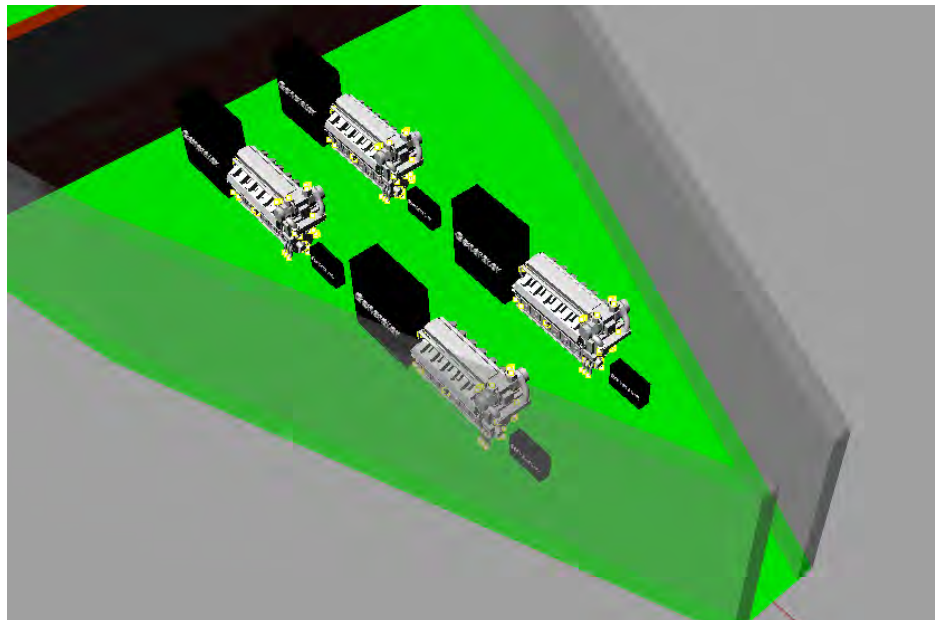


**Figure 6: Preliminary engine layout concept**

The second stage of engine selection opened up the consideration of using four to six smaller engines. Due to space requirements, the six engine option was ruled out of consideration. The two last options considered were (1) five Wärtsilä 9I34DF engines, which had the advantage of easier maintenance, or (2) four Wärtsilä 12V34DF engines, which had a smaller footprint.

In the end, four Wärtsilä 12V34DF engines were selected in order to minimize the weight. The final engine room layout is shown in Figure 7. The engine specification sheet can be found in Appendix D.

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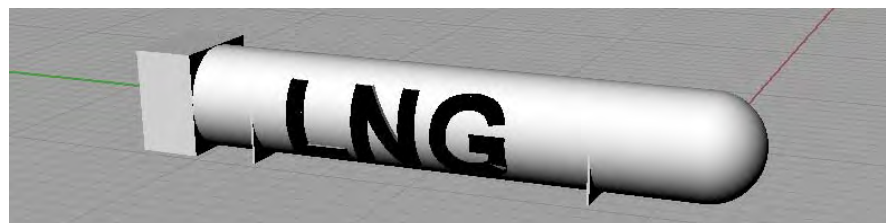


**Figure 7: Final engine layout**

The engines provide an installed power rating of 20,880 kW and a total footprint of 123.3 m<sup>2</sup>, which does not include space needed for the auxiliary systems and the void space required by regulation rules. A more detailed examination of powering estimates is located in Appendix E.

### *Storage Possibilities*

To successfully store LNG, it needs to first be cryogenically cooled to below its boiling point of -259°F. It is then placed into a double walled stainless steel tank at a pressure of 5bar. To be able to store LNG at this pressure, cylindrical tanks are typically used. For the RORO container/trailer carrier concept, six Wärtsilä LNGPac 284 tanks were chosen. These tanks have a diameter of 4.2m and a length of 27.1m, as shown in Figure 8. These tanks are placed in a 2 x 6 arrangement within the designated space in the vessel. The particular arrangement of these tanks is discussed later in this report.



**Figure 8: Selected LNG tank**

The cylindrical shape was chosen in order to avoid any stress concentrations in the tank material. The 4.3m diameter tanks were selected due to overhead height

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restrictions. Since the overhead clearance of the tank room was 4.7m, it was ensured that the selected tanks will fit within the vessel with minimal design alterations.

To explore what could be done to save even more space, several different tank shapes were investigated that were not commercially available. One promising idea consisted of using a regular cylindrical shape with rounded edges, as shown in Figure 9. Inside the outer wall, an internal structure was placed to ensure the strength of the tank and to avoid any stress concentrations and failure along the flat surface.

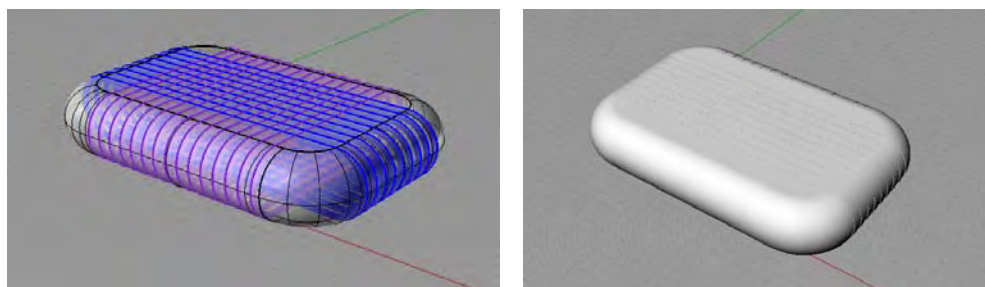


Figure 9: LNG tank concept design

By using a tank of this shape, the same volume of LNG can be carried while taking up much less space in the vessel. The volumetric efficiency of this tank concept is illustrated in Figure 10, where the required volume is carried in a much smaller area. Though no structural analysis has been done currently, it is recommended that this tank shape be further explored.

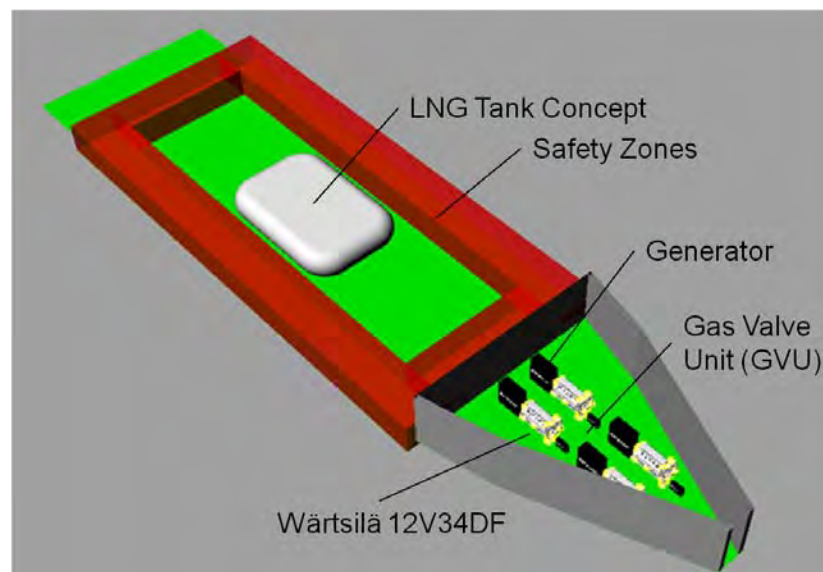


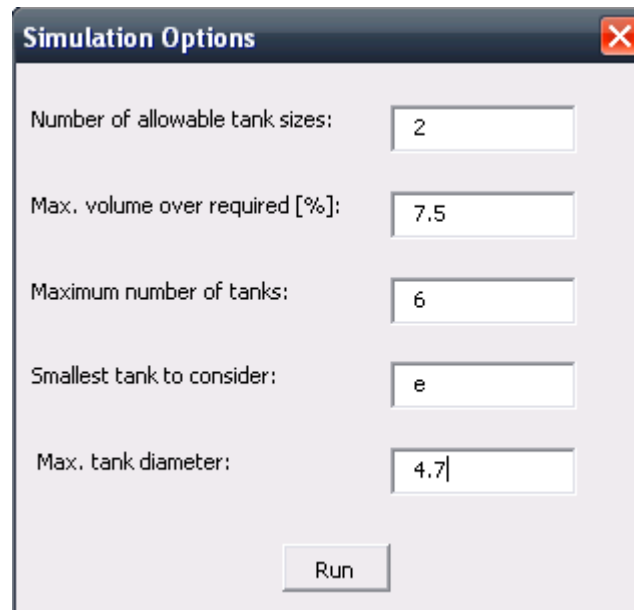
Figure 10: General arrangement with tank concept

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An alternative possibility for tank placement would be the use of open decked ISO containers. When LNG is being handled on an open deck, the ventilation requirements previously outlined are unnecessary. Added regulations state that the tanks are required to be located at a distance of B/5 (beam overall) from the side of the ship (with a minimum of 760 mm from the side). The tanks are also required to be supplied with drip trays to prevent leaked gas from making direct contact with the decks surface.

### Tank Options

With a variety of different tank sizes available, a tank selection tool was created to determine what combination of tank sizes would be appropriate for the RORO container/trailer carrier design. The selection tool is capable of various inputs such as number of allowable tank sizes, the maximum number of tanks, the maximum tank diameter, and the smallest tank to consider. The input window is shown in Figure 11. After determining the input variables, the tank selection tool displays a result of various tank size combinations that meet the required volume. As shown in Figure 12, utilizing six Wärtsilä LNGPac 284 tanks is deemed appropriate to use for the RORO container/trailer carrier concept design, and carries enough volume for a 5,599nm range.



**Simulation Options**

Number of allowable tank sizes:

Max. volume over required [%]:

Maximum number of tanks:

Smallest tank to consider:

Max. tank diameter:

Figure 11: Input form for tank size selection tool

	A	B	C	D	E	F	G	H	I
	Tanks	LNG Vol. [m3]	Max Tank Diam. [m]	Total Weight [t]	Actual Range [nm]	Footprint [m2]	# Tank Sizes	Pct. Over Vol.	Num. Tanks
1									
2	eeeeee	1534	4.3	1386	5599	777	1	6.6%	6

Figure 12: Results of tank size selection tool



## *General Arrangement*

HEC provided the team with a preliminary design of the RORO container/trailer carrier concept. The profile view at the starboard side looking inwards was used to reference the general arrangement of the vessel. The document containing the profile view can be found within Appendix B.

The design includes two separate machinery spaces: one forward and one aft, with space for LNG tank storage amidships. Additional details on the general arrangements of the container/trailer carrier can be found in HEC's data sheet located in Appendix A.

Two options for storing LNG tanks, either within enclosed deck storage or in containers located on the top deck, were considered. Upon receiving the design, the team was given the option of altering the area beneath the lower deck in the case of needing more space for the LNG tanks. Since it is extremely difficult to store trailers within this space, it was jointly decided that this cargo area could be converted to a storage tank room. By selecting appropriately-sized tanks, the vessel design did not need to be significantly altered, which was one of the original project objectives.

The tanks were selected in the manner discussed previously. Figure 13 illustrates the LNG tank and forward machinery room layouts, which includes the selected engines, generator sets, and gas valve units (GVU).

The red area of the drawing represents the safety areas where LNG tanks were not allowed to penetrate for several reasons. DNV rules state that tanks need to be located at least 7.12m (B/5) from the ship side, 2m from the bottom plating, and not less than 0.76m from the shell plating. These requirements are based on the requirement that gas hazardous areas must be secure from other safety zones. The proposed tank arrangement meets all of these requirements.

Within the forward engine room, the selected engines are shown complete with the appropriate generator sets and GVU. A spacing of 3.8m between the engine shafts is required for maintenance. The engine room arrangement has been designed accordingly. DNV rules should be referred to for more specific details on arrangement of tank and engine rooms.



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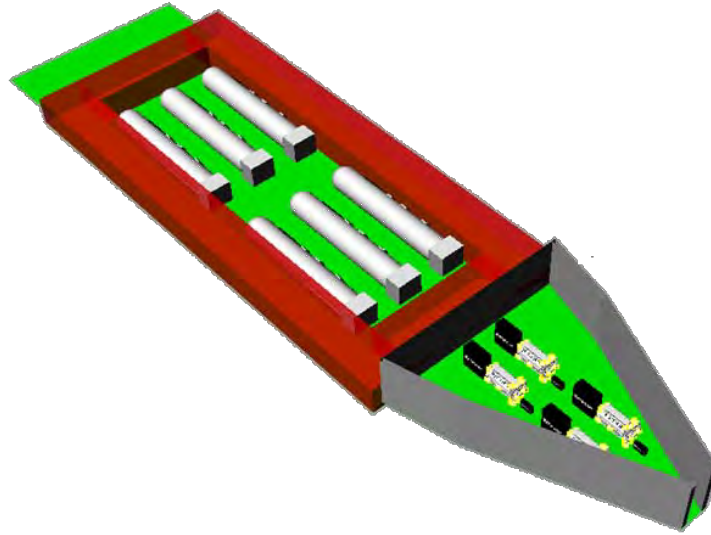


Figure 13: Propulsion system arrangement

### *Impact on Lightship Displacement*

One of the goals of the project was to explore the impact of installation of a NG propulsion system on the lightship weight. It was found that the only significant increase in weight results from the installation of slightly larger engines, and from the installed LNG tanks. Additional auxiliary systems were found to be of relatively small importance and would not be a large design driver. Table 2 illustrates the previous lightship weight breakdown as well as the alterations that were made. It should also be noted that the vessel will carry approximately 650 tons of LNG, corresponding to a 5000 nm range.



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ORIGINAL		
No.	Name	Weight MT
1	Aft Part - steel	494
2	Aft Machy Room - steel	1,283
3	Cargo Block - steel	6,039
4	Fwd Part - steel	1,641
5	House & Casing	429
6	Focsle	195
7	Poop Deck	553
8	Aft Machinery	562
9	Fwd Macinery	1,444
10	Hull Outfit	519
11	Cargo Gear/Hull Piping	468
12	Accomodation Outfit	223
	LightShip Margin	554
TOTAL:		14,404

MODIFICATIONS		
9a	Remove 2 x 12V32 + 2 x 8L32	-205
9b	4 x 12V34DF Genset	235
13a	2 x LNGPAC402 - aft	624
TOTAL:		15,058
Weight increase:		654

Table 2: Initial lightship displacement breakdown



## Electrical Diagram

A full illustration of the vessel's diesel-electric drive system is shown in Figure 14. The engines are directly connected to four electrical generators, which produce the main electrical power for the vessel. The power runs through the generator sets by high-voltage (HV) cables to two high-voltage switchboards supplied on the ship, which are used to send, stop, or distribute the flow of the power during operation. From the two switchboards, the power is capable of being delivered to the variable speed drives, electric motors, and the propellers.

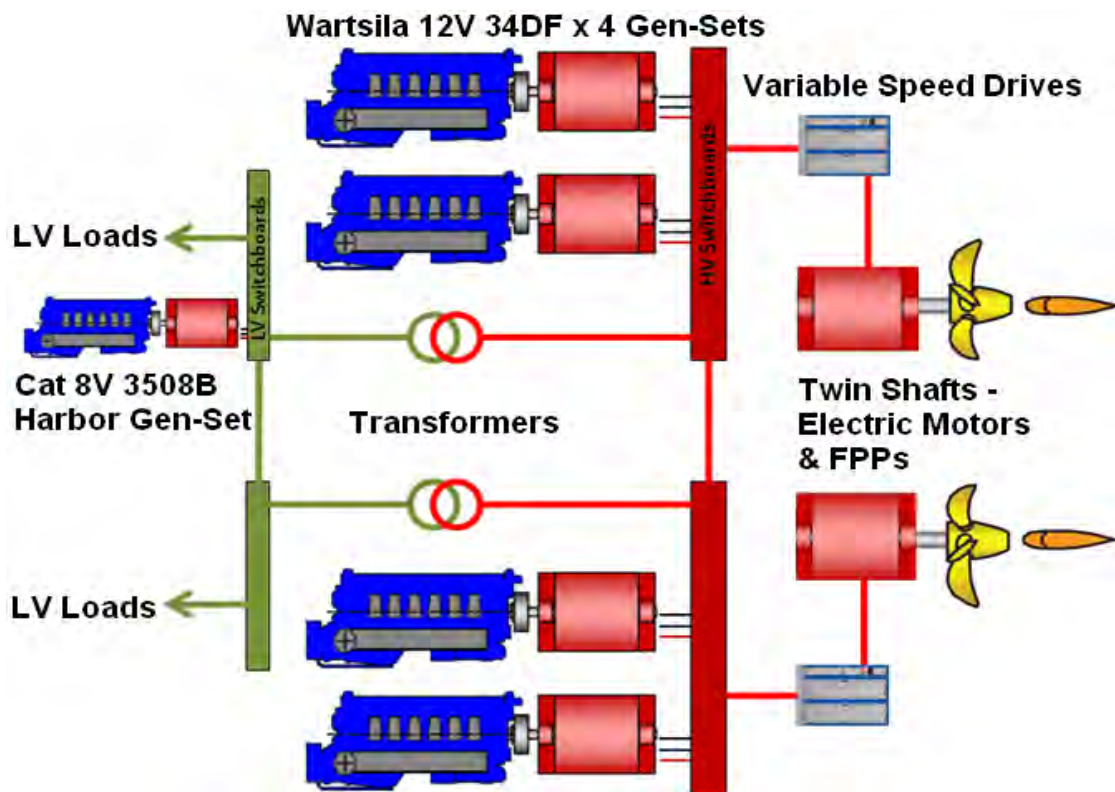


Figure 14: Dual-fuel engine electrical diagram

Courtesy: Andrew Tate, NSWCCD

## Cost Considerations

In addition to emissions benefits, using natural gas as a primary marine fuel offers significant cost benefits. Based on the prices of HFO, MDO, and NG on July 19<sup>th</sup>, 2010, the cost of LNG per 3000 nm voyage was found to be significantly lower than diesel alternatives. This cost comparison is shown in Figure 15.

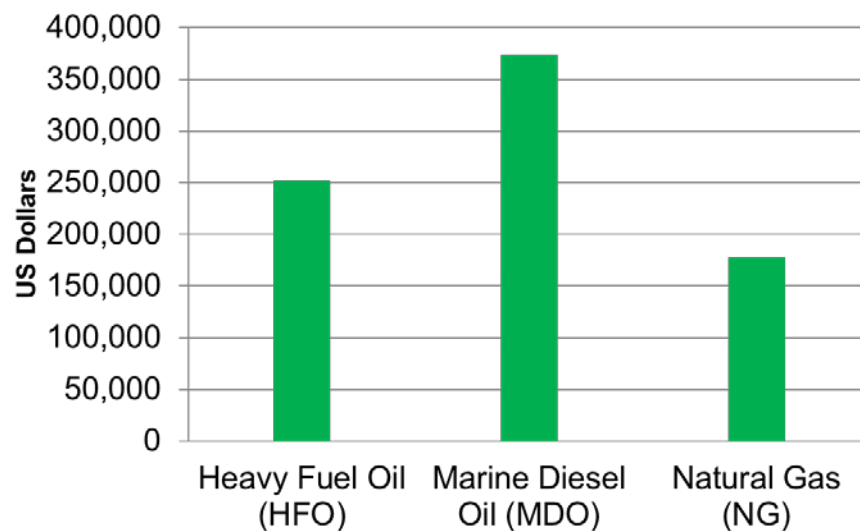


Figure 15: Natural gas price comparison

The price of HFO and MDO was found to be \$440/mt and \$655/mt from Bunker World. The prices of LNG at Henry Hub were found to be approximately \$303/mt on the same day. While this cost does not include the price of liquification, which will minimize the cost difference, it does highlight the economic advantage of using natural gas as the primary fuel.



## Conclusions

### *Concept Conclusion*

At the beginning of this study, the group was instructed to research both liquefied and compressed natural gas and the design integration issues concerning volume, storage, and the design of cryogenic storage systems. Specifically for the HEC RORO container/trailer carrier, it was decided that CNG is impractical as a fuel option due to the large volume required to store it effectively. It has been found that the storage of LNG is a feasible and attractive choice for the container carrier design with relatively small impact on the overall vessel design.

There are a number of indications that natural gas can be an effective fuel choice for commercial vessels. Research has shown that natural gas is safe when appropriately handled, and its use effectively reduces emissions significantly. These emission reductions meet the Tier III IMO emission requirements. Additionally, natural gas is an economical choice when comparing it to other marine fuels such as HFO and MDO.

Marine engines that run on natural gas are readily available on the commercial market and many manufacturers offer full natural gas propulsion solutions. There is also a very large potential for future availability of natural gas, with a number of import existing terminals and awaiting approval and potential for natural gas refueling stations to be constructed in the future. This, combined with the availability of natural gas within U.S borders, makes it an attractive option for commercial and military uses alike.

### *Recommendations*

The results of this project strongly warrant a more detailed examination of natural gas for marine propulsion. Particularly, different tank shape concepts must be structurally evaluated for their capability of withstanding the high pressure at which natural gas is stored. Tank concepts other than the basic cylinder show a large potential to save a large amount of space, which would make natural gas an even more attractive option.



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## Appendices

### Appendix A – Vessel Particulars

Particular	Dimension
Length, overall (LOA)	180.3 m
Length, between perpendiculars (LBP)	172.0 m
Beam	36.6 m
Depth to Main Deck	12.9 m
Depth to Upper Deck	18.5 m
Design draft	6.70 m
Summer Load Line Draft	7.62 m
Deadweight at Design Draft	13,573 mt
Lightship Weight	14,400 mt
Accommodations	25 persons
Crew (Estimated operating crew)	18 persons
Speed (15% sea margin) at Design Draft	18 knots
Propulsion	Diesel Electric, Twin Screw
Installed Power	≈ 20,000 kW
Range at Design Draft & Design Speed with 3 days fuel reserve	13,600 n.m.
Fuel Capacity (MGO)	3,200 m <sup>3</sup> (2,720 mt at s.g. 0.85)
Ballast Capacity	13,080 m <sup>3</sup>



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*Hull Form and Stability*

Item	Dimension
Block Coefficient at Design Draft	0.65
Length/Beam	4.70
Length/Depth	9.30
Beam/Draft	5.46
GM at Full Load Arrival Condition	8.2 m
LCB at Design Draft	About 4% fwd of Midship
Stern Type	Twin Propeller Skegs with Centerline skeg
Bow Type	Bulbous Bow
Deckhouse	Forward
Principal Machinery	Forward



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*Cargo Capacity and Equipment*

Item	Dimension
RORO Area	16,500 m <sup>2</sup>
<i>Max Trailer Capacity Stowage Arrangement</i>	
53' Trailer Capacity at Max Trailer Capacity	242 units (229 with LNG propulsion)
Container Capacity at Max Trailer Capacity	0 units
Total Number of Cargo Units	242 units (229 with LNG propulsion)
Cargo Weight at 20 m. tons per unit	4,480 mt (4,580 mt)
<i>Max Container Capacity Stowage Arrangement</i>	
53' Trailer Capacity at Max Container Capacity	181 units (168 with LNG propulsion)
Container Capacity at Max Container Capacity	194 units (53' & 40'/45')
Total Number of Cargo Units	375 units (362 with LNG propulsion)
Cargo Weight at 20 m. tons per unit	7,500 mt (7,240 mt)
<i>Cargo Data</i>	
Maximum Trailer Weight	30 mt (66,000 lbs)
Maximum Container Weight	30.5 mt (67,000 lbs)
Reefer Trailers & Containers	75 units
Electric Power at 7 kW each Reefer	525 kW
Clear Deck Height, Main Deck & Below	4.75 m
Clear Deck Height, Upper Deck, under 01 Level	7.2 m
Hazardous Cargo, Upper Deck, 01 Level, except forward most container group	All Classes
Hazardous Cargo, Main Deck, aft of Forward Mach. Space (Fr 150)	All classes, except Class 1 Explosives (but including Class 1.4S)
Hazardous Cargo, 2 <sup>nd</sup> Deck, Tanktop, Main Deck fwd	None



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*Strength*

Item	Dimension
Estimated Section Modulus, Midship	11.1 m <sup>3</sup>
Still Water Bending Moment, Midship	150,000 t-M
Trailer Deck Strength, Tanktop, 2 <sup>nd</sup> Deck, 01 Level	1.46 mt/m <sup>2</sup>
Trailer Deck Strength, Main Deck, Upper Deck (for M1A Tanks and large military vehicles)	1.95 mt/m <sup>2</sup>
Axle Load, Maximum, Main & Upper Deck Other Decks	14.5 mt (32,000 lbs) 9.0 mt (20,000 lbs)
Tire Load, Maximum, Main & Upper Deck Other Decks	7.25 mt (16,000 lbs) 4.5 mt (10,000 lbs)
Container Stack Weight, Upper Deck	75 mt (165,000 lbs)
Max Weight, Container Cassettes	65 mt (143,000 lbs)





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*Ramps*

Item	Dimension
Ship based Stern Quarter Ramp, non-WT, Main Deck, Transom-Fr. 10, starboard	Clear opening width: 14.5 m Opening clear height: 4.75 m Min. clear width: 8.5 m Outreach: 32 m Design Load: 1.95 mt/m <sup>2</sup> Axle Load: 14.5 mt (32,000 lbs)
Shore Side Ramp Opening, non-WT, Main Deck, Fr. 9097, starboard	Clear width: 6.6 m Opening clear height: 4.75 m
Shore Side Ramp Opening, non-WT, Upper Deck, Fr. 27-37, starboard	Clear width: 8.0 m Opening clear height: 7.15 m
Internal Ramps, Fixed or Hoistable	Clear width: 5.0 m Clear height: 5.0 m Design Load: 1.46 mt/m <sup>2</sup> Axle Load: 9.0 mt (20,000 lbs) Slope: max 10 degrees

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*Deck and Auxiliary Machinery*

Item	Dimension
Optional Crane – SWL	40 mt
Optional Crane – Outreach	27 meters
Mooring Winches, Forward	15 mt x 15 m/min Rope hawser, autotension 2 x Single Drum type, attached to Windlass 1 x Single Drum type, on centerline
Mooring Winches, Aft	15 mt x 15 m/min Rope hawser, autotension 4 x Single Drum type, 2 port & 2 starboard
Ballast System	Ring Main Type Pumps: 2 x 750 m <sup>3</sup> /hr
Anti-Heel System	Pump 1 x 900 m <sup>3</sup> /hr Axial flow type WBT 3 Port & 3 Starboard: Anti-heel tanks
Ballast Water Treatment	Provided
Enclosed RoRo Space Ventilation System, Tanktop, 2 <sup>nd</sup> deck & Main deck spaces	Mechanical exhaust and natural supply, 6 air change per hour per SOLAS rule.
Covered RoRo Space Firefighting System	Fixed Water Spray System with proper drainage provided.
RoRo Space Electrical Equipment	Explosion proof type
RoRo Space Bilge System (Tanktop & 2 <sup>nd</sup> Deck Spaces). Main and Upper Deck to drain directly overboard	Separate bilge system, outside of the Machinery Space, with separate pumps
Tug Push Areas with hull marking	3 Port, 3 Starboard, Fwd, Midship, Aft

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*Propulsion*

Item	Dimension
$P_D$ – Power at propeller at 18 knots, 90% MCR and 15% sea margin at design draft	15,100 kW
Propeller type, 2 provided	Fixed Pitch
Propeller Diameter	4.5 m
Maximum RPM	About 180
Assumed efficiency of gearbox and shafting	97%
BkW at Electric Motor output (assume high speed motor with gearbox) at design speed at design draft, 15% sea margin	15,570 kW
BkW of each motor	7,785 kW
Assumed efficiency of Electric Drive	93%
Generator Output for design speed	16,740 kW
Estimated Sea Going Electric Load	800 kW
Total Required Generator Output	17,540 kW
Assumed Generator Efficiency	97%
Diesel Engine Output at 90% MCR	18,085 kW
Diesel Engine Output at 100% MCR	20,000 kW
Fuel Type, USA ECA Compliant, 2015 and later	Distillate Diesel Oil (MGO type), ISO 8217 type DMA, 0.1% Sulfur Maximum
Specific Fuel Consumption (SFC) with Diesel Oil	185 g/kW/hr (176 maker SFC + 5% maker margin)
Daily Fuel Consumption at 90% MCR	80 mt/day
$P_D$ – Power at propeller at 15 knots, 15% sea margin at design draft	8,740 kW
Total Diesel Engine Output at 15 knots (including 800 kW ship's electrical power)	10,815 kW
Daily Fuel Consumption at 15 knots	49 mt/day
MAN Engine Types 2 x 12V32/33CR 2 x 6L32/44CR Total Installed kW	2 x 6,720 kW 2 x 3,360 kW 20,160 kW
Wärtsilä Engine Types 2 x 12V32 2 x 8L32 Total Installed kW	2 x 6,000 kW 2 x 4,000 kW



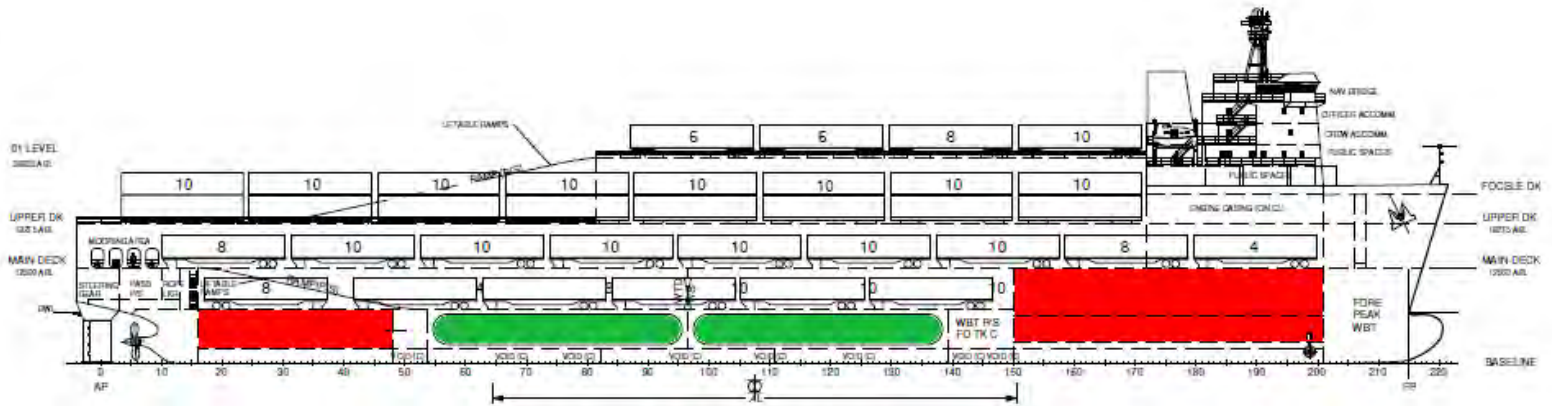
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	20,000 kW
Harbor Generator Output, 1800 rpm type	800 kW, 440 V
Main Generator Voltage	6.6 kV x 3 phase
Ship's Service Electrical Voltage	440 V x 3 phase
Boiler & Steam System	Not provided since fuel heating is not required.
Bow Thruster, Controllable Pitch Type	1 x 1,200 kW
Rudders	2 x High Performance type
Steering Gear	Rotary Vane Type

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## Appendix B – Profile view

Red sections represent the forward and aft machinery rooms. Green sections represent the preliminary natural gas tank locations.







## *Appendix C – Import Terminal Locations*

### 1. Existing Locations:

- a. Everett, Massachusetts
- b. Cove Point, Maryland
- c. Elba Island, Georgia
- d. Lake Charles, Louisiana
- e. Gulf Gateway Energy Bridge, Gulf of Mexico
- f. Northeast Gateway, Offshore Boston
- g. Freeport, Texas
- h. Sabine, Louisiana
- i. Hackberry, Louisiana

### Approved Locations (unconstructed):

- a. Federal Energy Regulatory Commission (FERC):
  - i. Corpus Christi, Texas (Three Locations)
  - ii. Fall River, Massachusetts
  - iii. Port Arthur, Texas
  - iv. Logan Township, New Jersey
  - v. Cameron, Louisiana
  - vi. Freeport, Texas
  - vii. Hackberry, Louisiana
  - viii. Pascagoula, Mississippi
  - ix. Port Lavaca, Texas
  - x. LI Sound, New York
  - xi. Bradwood, Oregon
  - xii. Baltimore, Maryland
  - xiii. Coos Bay, Oregon
- b. MARAD/Coast Guard:
  - i. Port Pelican
  - ii. Gulf of Mexico



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iii. Offshore Florida

Proposed Locations:

- a. Federal Energy Regulatory Commission (FERC):
  - i. Robinson, Maine
  - ii. Astoria, Oregon
  - iii. Calais, Maine
- b. Maritime Administration (MARAD)/Coast Guard:
  - i. Gulf of Mexico
  - ii. Offshore Florida
  - iii. Offshore New York

Not Yet Formally Proposed:

- a. Offshore California (two Locations)
- b. St. Helens, Oregon
- c. Philadelphia, Pennsylvania
- d. Offshore New Jersey (two Locations)

## Appendix D – Engine Specifications

### WÄRTSILÄ Engines

#### WÄRTSILÄ 34DF

#### IMO Tier II

##### Main data

Cylinder bore ..... 340 mm  
Piston stroke..... 400 mm  
Cylinder output..... 450 kW/cyl  
Speed ..... 750 rpm  
Mean effective pressure ..... 19.8 bar  
Piston speed..... 10.0 m/s

##### Fuel specification:

Fuel oil ..... 700 cSt/50 °C  
7200 sR1/100 °F  
ISO 8217, category ISO-F-DMX,  
DMA and DMB

##### Natural gas

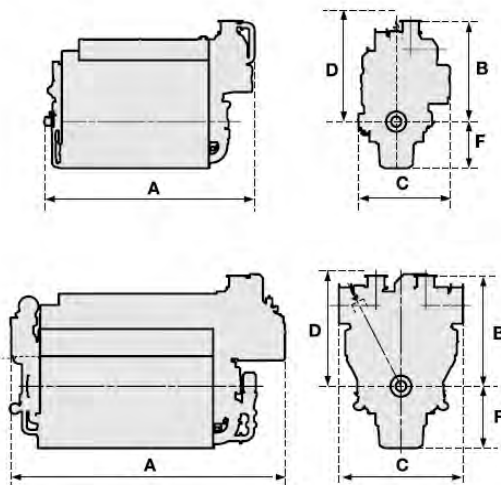
Methane number: 80  
LHV: min. 28 MJ/Nm<sup>3</sup>, 4.5 bar  
BSEC 7700 kJ/kWh

Rated power	
Engine type	kW
6L34DF	2 700
9L34DF	4 050
12V34DF	5 400
16V34DF	7 200

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Engine dimensions (mm) and weights (tonnes)						
Engine type	A	B	C	D	F	Weight
6L34DF	5 280	2 550	2 305	2 345	1 155	34
9L34DF	6 750	2 550	2 305	2 345	1 155	47
12V34DF	6 615	2 665	3 020	2 120	1 475	59
16V34DF	7 735	2 430	3 020	2 120	1 475	75

For definitions see page 68.



## Appendix E – Powering Estimations

Power comparison of MCR for American Marine Highways (AMH) Vessel

Power estimates for rail car carrier

0% Sea Margin (Trial Condition)			
Speed	SSPA (0.72)	MAN (0.72)	$C_b = 0.65$
10		3,085	
11	3,202	3,767	
12	4,217	4,621	
13	5,443	5,700	
14	6,910	7,046	7,010
15	8,665	8,732	8,622
16	10,749	10,829	10,858
15% Sea Margin (Operating Condition)			
Speed	SSPA (0.72)	MAN (0.72)	$C_b = 0.65$
10		3,547	
11	3,682	4,333	
12	4,850	5,314	
13	6,262	6,555	
14	7,947	8,103	8,062
15	9,969	10,042	9,915
16	12,371	12,453	12,487
<b>18</b>	<b>18,141</b>	<b>18,261</b>	<b>15,100</b>



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Calculated Losses			
<b>18 KNOTS</b>	<b>18,141</b>	<b>18,261</b>	<b>15,100</b>
Shaft/Gear Eff.	0.97	0.97	0.97
BkW at Motor	18,702	18,826	15,567
Elec. Drive Eff.	0.93	0.93	0.93
NCR/MCR	0.90	0.90	0.90
Elec. Load	800	800	800
MCR Diesel El.	23,144	23,293	<b>19,399</b>

Previous engines selected by HEC: Wärtsilä 2 x 12V32 and 2 x 8L32 Gen Sets



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